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A hydrogen future for Denmark

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Abstract

The components of the Danish hydrogen energy programme are presented, along with scenarios for the introduction and future use of hydrogen in the energy system. The Danish energy system is presently including about 12% power from wind, but the government's energy plan considers this to increase to near 50% by year 2030. As the wind power production during periods of high wind can be 3-4 times the average, it is expected that production will greatly exceed demand during such periods. If the surplus coincides with European peak electricity-use hours, the surplus may be exported through the already existing considerable international cable connections. However, if the market price is low (such as during off-peak hours), it is considered better to use the surplus to produce hydrogen. This hydrogen attains the highest value if used in the transportation sector. Therefore a scenario is constructed, in which infrastructure for use of hydrogen-fuelled vehicles is developed.

Keywords: Hydrogen utilisation, hydrogen distribution, wind energy, simulation, storage

1. Danish hydrogen energy programme

The Danish hydrogen energy programme was established in 1998, with the purpose of demonstrating concrete possibilities for hydrogen technologies in the future energy system. Research in hydrogen-related technologies such as fuel cells had already been ongoing for about 20 years through the Danish energy research programme. The Danish Energy Agency administers both programmes [1].

Components in the hydrogen energy programme are use of hydrogen in the transportation sector, hydrogen storage, safety and planning issues. The programme involves three hydrogen fuelled vehicles: A retrofit gasoline passenger car with a new hydrogen injection system, a de Nora proton exchange membrane (PEM) fuel cell driven Fiat electric passenger car, and a fuel cell driven MAN bus based upon liquid hydrogen stores. The Danish company IRD is developing the control system for the de Nora/Fiat car, an early concept drawing of which is shown in Figure 1.

Two storage tanks are developed as part of the programme, both suited for vehicle application. One is a 20 MPa compressed gas hydrogen container built from a number of cylindrical containers made of a lightweight fibre composite material, the other a 20

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Nm^3 metal hydride store e.g. based on titanium-zirconium alloys (other options are also investigated). The stores will be tested in the vehicles produced as part of the programme. Security evaluations will be made of all the hydrogen systems.

Finally, conditions for introducing hydrogen in the Danish energy system are determined, and a variant of the official Danish energy plan for the development to year 2030 is being constructed in order to include hydrogen as an energy carrier in the roughly 50% renewable energy based future energy system. In order to examine the constraints placed by very large renewable energy components, the scenario is carried further to year 2050, in order to investigate the functioning of the system when renewable energy contributions approach 100%.

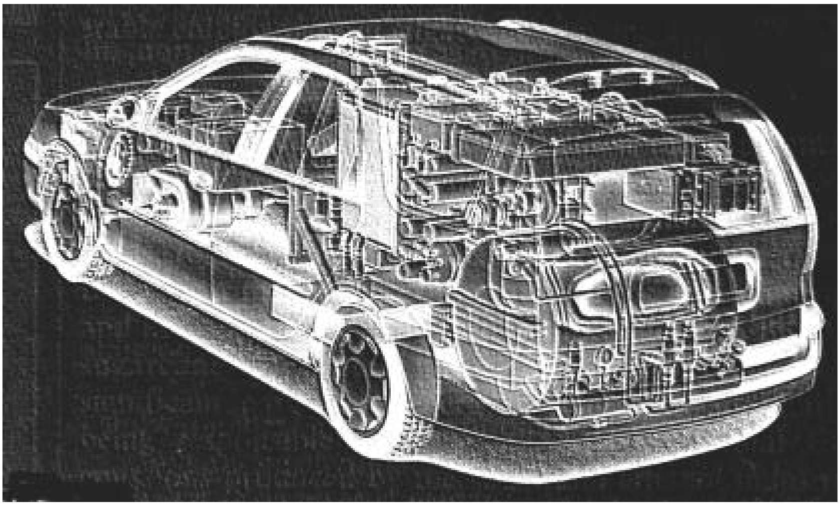

Figure 1. Concept for the Danish-Italian hydrogen vehicle collaboration: de Nora PEM fuel cells built into a Fiat electric car using IRD control equipment [2].

2. Dealing with fluctuations in wind power production

Wind power currently covers 12% of electricity use in Denmark, and the official energy plan [3] calls for a continued expansion, reaching around 50% by year 2030 and continuing to rise. The smooth integration of a variable renewable energy source into the energy system is thus a high-priority challenge for research and planning. A typical wind turbine today has a rated power of 2 MW and an annual average production of about 700 kW. This means that the entire system should be able to handle a major component, that sometimes produce zero power and sometimes three times the average, fairly independent of power demand (there is a minor positive correlation between wind power production and demand, both on a seasonal scale and on a diurnal scale). There are three basic ways of handling these variations:

i) Having a back-up system available. This is the situation today, where a combination of large coal-fired units and smaller natural gas-fired units provide backup for both planned and unplanned fluctuations in wind power production. This is possible due to the short upstart times (minutes) of gas turbines, and the reasonably fast regulation possible with modern boiler units using e.g. powdered coal as a fuel. However, there are two reasons that this solution is not considered viable for the future. One is the greenhouse gas mitigation policy, which requires fossil plants to be phased out over the next 25-30 years. The other is the growing share of wind in the electricity system, which increasingly makes it impossible to use a three times average power output.

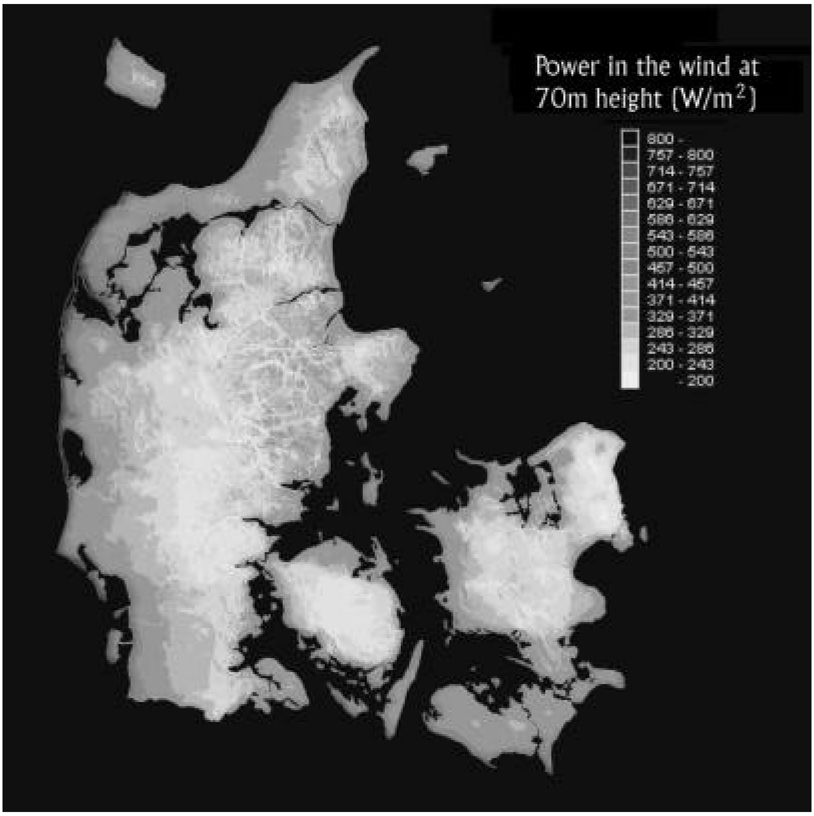

Figure 2. Average power in wind over land (W/m^2; height 70m above terrain) [6,7].

ii) Making use of import/export opportunities. Denmark has sizeable power transmission lines to Norway, Sweden and Germany and is currently engaged in both bulk sales across the boundaries and short-term trade on the Nordic “power pool” (an auction facility). It has been proven, that use of these facilities to deal with deficits and surpluses in wind production can handle all problems associated with fluctuating wind power generation, at a cost of only around 11% of the average trading price at the pool [4].

iii) Adding dedicated energy storage to the system. The future Danish energy system is already assumed to contain a component of biofuels, i.e. biogas of liquid fuels such as ethanol or methanol produced from residues from agriculture and forestry. They could serve as backup for wind energy, much as the fossil fuels do today, but as stated above, the magnitude of adjustments will increase and further options are likely to be required. This is likely to call for the use of hydrogen as storable energy, as hydrogen can be produced from excess wind power by electrolysis or by reverse fuel cells. If other forms such as methanol are found to be preferable, it is still likely that they would be secondary products produced on the basis of hydrogen.

Figure 2 shows the annual average power in the wind over Denmark. For suitable off-shore locations, the power may exceed the best found on land. Five such off-shore localities have been identified and set aside for wind power development. The total wind power production obtained from only using environmentally acceptable areas (essentially those presently having individual wind turbines or wind parks, plus the designated off-shore sites) exceeds future Danish power needs and leaves a possibility for net export [5].

3. Using hydrogen in the transportation sector

The observations on the future Danish energy system made above suggests that there will be a large amount of electricity available, provided that the relative short-term variations (related to passage of weather fronts, a typical time-scale being 2 weeks) can be handled. Electricity can be used for dedicated purposes, for process and other heat (through heat pumps), and it is only for the transportation sector that there seems to be limits to the use of electricity, at least using battery-driven vehicles. Therefore new fuels, whether biofuels (which are CO_2 neutral) or hydrogen, are thought of as mainly penetrating the transportation sector. One possibility would be battery-driven urban vehicles combined with hydrogen-fuelled vehicles for use outside the urban areas.

We are considering two possible ways of supplying hydrogen to road-based vehicles. One is to convert the existing petrol filling stations to deliver hydrogen or methanol (the latter being a minor modification, the former a more substantial one). Hydrogen would be produced at fairly large plants with access to surplus wind electricity, and distributed through the transmission lines currently used for natural gas. Some upgrading of the gas handling equipment is foreseen [6]. The set-up is illustrated in Figure 3.

The other possible future development is highly decentralised: Here many buildings will have installed reversible fuel cell equipment, enabling them to co-produce power and heat, to export excess power through the electricity grid, or to produce hydrogen from it. This option is available for clients to the hydrogen distribution network, i.e. the present natural gas customers plus those that might be added as the system expands. Figure 4 shows the location of present natural gas customers and the overall gas transmission system. A possibility is that these decentralised producers may be able to fill their vehicles with hydrogen produced on the spot. Considerations of safety should be included in weighing the two alternatives.

4. Discussing transitional problems

The method used to discuss the possible future role of hydrogen in the Danish energy system is geographical and time modelling, where energy use and supply are being specified per unit of area, and with time profiles over several years, with emphasis of variations between years, seasonal variations, and variations during the hours of the day. In this way requirements for hydrogen supply and transfer to vehicle storage tanks can be simulated, and the technical consistency can be discussed as function of the relative capacities of components, such as hydrogen production and storage facilities. The scenario model includes a similar discussion of stationary uses of the available hydrogen, e.g. distributed through a slightly modified existing natural gas network and delivered to stationary fuel cells producing both heat and power on a decentralised scale. As several components in the systems considered are still under development, we have chosen a fairly extended transition period (30-50 years), leaving room for accomplishing infrastructure changes when existing system are anyway to be decommissioned.

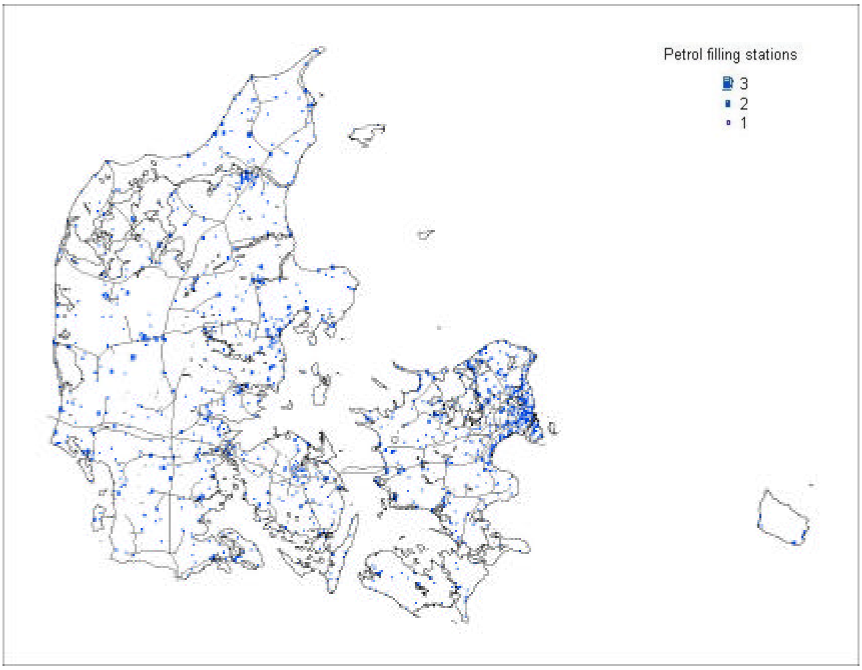

Figure 3. Location of petrol filling stations (by stochastical model with correct total and spread; in a few cases there are more than one in a 500m×500m cell). Current gas transmission lines are shown (but not local distribution network) [6].

One important question being addressed is the degree of decentralisation considered optimal. Fuel cell technologies are currently developing in more than one direction, but with the most likely early (economic) breakthrough for PEM cells to be used by vehicles in the transportation sector. This may make small PEM cells of interest for stationary uses as well, although in theory, a higher efficiency should be obtainable with technologies using higher working temperatures. One advantage of low working temperatures for stationary uses is that this makes fuel cells interesting for use in individual buildings including domestic residences. We develop this idea further in one separate scenario, where even distribution of hydrogen (or derived methanol) to vehicles is done decentralised. Still, the distribution from existing, renovated filling stations is probably the more likely scenario. It can be accomplished with little more inconvenience than earlier changes between different gasoline types. As for the decentralised scenario, it will require a transition from natural gas to hydrogen in local gas distribution systems, a transition than has to be done in one step, at least for each region of supply.

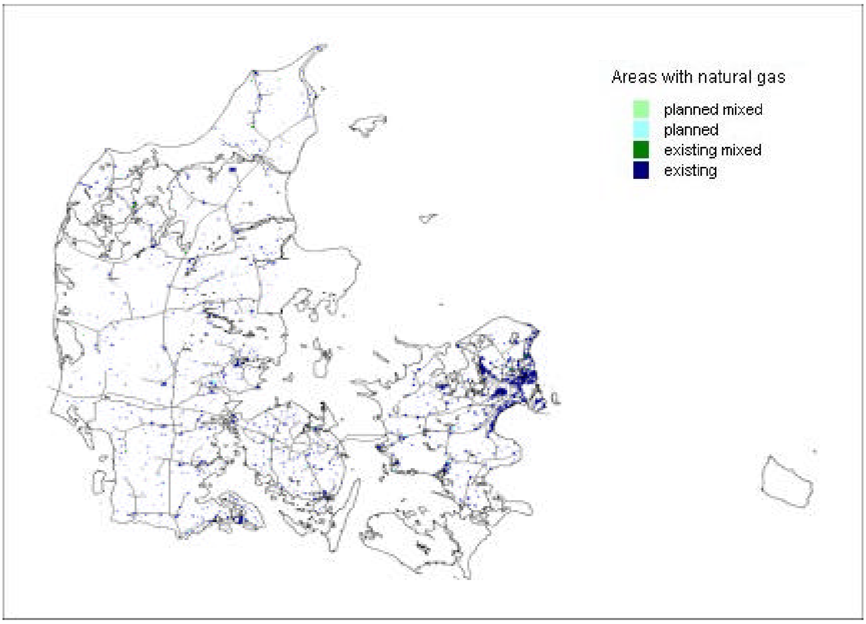

Figure 4. Location of current natural gas supply areas and planned expansions (some are "mixed" and can supply heat by district heating as well) [6].

Acknowledgements

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